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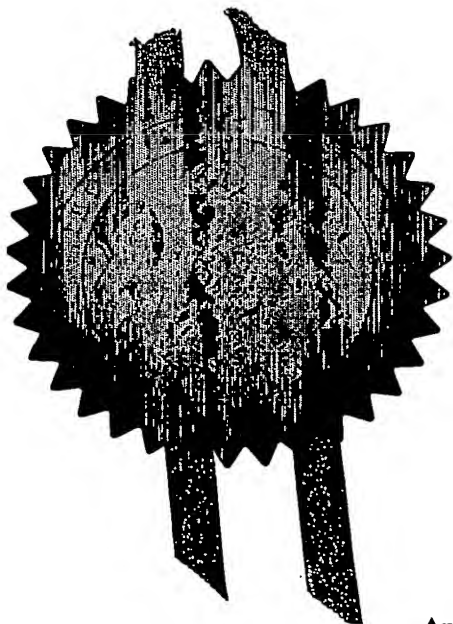
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0314357.5

19 JUN 2003

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PII LTD  
ATLEY WAY  
CRAMLINGTON  
NORTHUMBERLAND  
NE23 1WW, GB

Patents ADP number (if you know it)

If the applicant is a corporate body, give the country/state of its incorporation

GB

8458465001

4. Title of the invention

ELECTROMAGNETIC ACOUSTIC TRANSDUCER

5. Name of your agent (if you have one)

"Address for service" in the United Kingdom to which all correspondence should be sent (including the postcode)

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York House  
23 Kingsway  
London WC2B 6HP

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Claim(s)

Abstract

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ELECTROMAGNETIC ACOUSTIC TRANSDUCER

This invention relates to electromagnetic acoustic transducers (hereinafter referred to as EMATS) for inspecting the integrity of metallic components, for example gas pipelines, by ultrasonics.

Conventional EMATs interact with test materials by the joint action of a steady magnetic field, often produced by one or more permanent magnets, and a transient high frequency magnetic field, produced by an electrical winding. The interaction of the EMAT with the test specimen is usually at a maximum when the gap between the active components of the transducer and the test material is at a minimum.

However, EMATs are subjected to wear if moved while in contact with a test material.

Consequently EMATs to be moved along the surface of a test material require the provision of a protective layer or wear plate between the active components of the EMAT and the surface. This layer is subject to conflicting requirements. Wear resistance improves as layer thickness increases, but the acoustic performance of the EMAT decreases as the layer thickness increases, and is dependent upon the material properties and geometry of the protective layer.

The materials of protective layers usually incorporated in EMATs are chosen to have a negligible interaction with the EMAT, their presence having no other effect on acoustic performance than that associated with introducing an unfilled gap between the active face of the EMAT and the test material. Protective layers made from these materials are typically very thin, because EMAT acoustic performance falls very sharply as the gap increases. Since the material is thin, the lifetime of the wear layer can be short if the abrasion it experiences is particularly severe, for example in long distance high speed inspection of a pipe wall from an internal inspection vehicle or pipeline pig.

The use of electrically conductive and/or ferromagnetic material for the protective plate has heretofore been outlawed because the acoustic performance of the EMAT is severely reduced if a plate of such material is interposed between the EMAT and the material under test.

More particularly the presence of such a plate significantly reduces the penetration of the high frequency magnetic field from the EMAT into the test material due to the electrical skin depth phenomenon, and the DC magnetic field in the test material is reduced due to the removal of D C Flux from the test material by alternative closure paths.

In view of the excellent wear characteristics of some such materials, it would be desirable if wear plates having electrically conductive and ferromagnetic characteristics could be incorporated into EMATs whilst maintaining an effective acoustic performance from the EMAT.

According to the present invention there is provided an electromagnetic acoustic transducer for exciting ultrasound in a material under test, the transducer comprising magnetic means for applying a DC magnetic field to the material under test, an electrical winding supplied by an alternating current source for providing an AC magnetic flux within the material under test, and a wear plate adapted to engage with and slide along the surface of the material under test, characterised in that the wear plate comprises an electrically conductive, ferromagnetic material having apertures therein configured to provide electrical and magnetic discontinuity in the wear plate and to permit penetration of both the DC magnetic field and the AC magnetic flux into the material under test so as to create, by their interaction, ultrasonic vibration of the material under test.

The precise configuration of the apertures in the wear plate is chosen to suit the type of EMAT and to ensure the establishment of the DC magnetic field and the AC magnetic flux in the material under test.

A wear plate of an electrically conductive, ferromagnetic material of an EMAT according to the invention can be arranged to have a thickness greatly in excess of conventional non-ferromagnetic, non-electrically  
5 conductive wear plates whilst still maintaining acoustic efficiency. This increased thickness and wide choice of material properties for the wear plate allows the operating life of the EMAT to be increased above that possible with conventional wear plates.

10 In one embodiment of the invention, the apertures comprise a plurality of parallel slots in the wear plate each extending substantially perpendicular to the direction of image current flow in the material under test.

In a transducer according to the invention of which  
15 the magnetic means comprise a plurality of longitudinally aligned magnets adjacent ones of which have opposite poles abutting one another, it is preferred that the slots are located below the boundaries between adjacent magnets.

Preferably the thickness of the wear plate is equal to  
20 one quarter of the wavelength of the main wave mode excited within the wear plate.

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By way of example only, an embodiment of the invention will be described in greater detail with reference to the accompanying drawings of which:

Fig. 1 shows part of a conventional EMAT with no wear plate between an electrical winding and a material under test;

Fig. 2 shows the arrangement of Fig. 1 with an electrically conductive plate interposed between the winding and the material under test;

Fig. 3 shows part of a conventional EMAT with magnetic means applying a DC magnetic field to a material under test;

Fig. 4 shows the arrangement of Fig. 3 with an electrically conductive plate interposed between the magnetic means and the material under test;

Figs. 5 and 6 show parts of an EMAT according to the invention, and

Fig. 7 shows part of a preferred embodiment of the invention.

Referring to the drawings, Fig. 1 is an illustration of the AC currents produced by a simple winding such as might typically be used in an EMAT for generating horizontally polarised shear waves. It shows a planar winding 2 above a test sample 4. An AC current passes through the winding and is indicated by current flow arrows 6. These current flows are shown frozen in time, circulating in one arbitrary direction. Image currents 8 are induced into the test sample 4 by the AC winding



currents 6 and are in the opposite direction to the AC winding currents 6. They circulate within a plane on the top surface of the test sample 4.

Fig. 2 shows the effect of introducing an electrically  
5 conductive plate 10 between the winding 2 and the test sample 4. The image currents 8 now flow in the surface of the conductive plate 10. Unless the conductive plate 10 is very thin or has poor conductivity, it will shield the test sample 4 from the electromagnetic effects of the winding 2  
10 and prevent the circulation of any image currents within the test sample 4. This would prevent the EMAT, which is only partially illustrated in Fig 2, from functioning.

Fig. 3 shows the DC field pattern in the surface of the test sample 4 created by permanent magnets 12,  
15 positioned in a typical arrangement for a horizontally polarised shear wave EMAT. The test sample 4 is shown with areas of differing polarity 14 for the normal magnetic field component in the test sample 4. Fig. 3 shows all the key components of the most commonly used design of  
20 horizontally polarised shear wave EMAT.

Fig. 4 shows the effect of introducing an electrically  
conductive plate 10 between the magnets 12 and the test  
sample 4, the DC magnetic field previously established in  
the test sample 4 being trapped in the plate 10 and not  
25 reaching the test sample 4.

According to the EMAT of the invention, there is provided an electrically conductive ferromagnetic wear plate with apertures therein configured to create electrical and magnetic discontinuity in the wear plate and to permit penetration of both the DC magnetic field and the AC magnetic flux into the material under test so as to create, by their interaction, ultrasonic vibration of the material under test.

Fig. 5 shows the effect on the AC current of introducing a slotted electrically conductive plate 16. The plate 16 is shown only in part, namely the region of the slots where the plate 16 appears to be a series of bars, numbering three for the purposes of illustration. The slots are arranged broadly perpendicular to the normal flow of image currents 18 in the conductive plate 16. In this case, image currents flow in both the conductive plate 16 and in the test sample 4, where the direction of flow is similar to the simple case in Fig 1. In the slotted plate 16, the image currents 18 are forced to travel down the walls of the slots and complete their circuit by travelling along the lower surface of the plate 16 (not visible in Fig. 3) in the opposite direction to the flow on the top surface of the plate 16.

In Fig. 5, the image currents 8 in the test sample 4 can be of higher amplitude than those in Fig. 1, even for

an equivalent winding current amplitude and for an equivalent distance between the winding 2 and the test sample 4. This is particularly true when the thickness of the slotted plate 16 occupies a large proportion of the gap between the winding 2 and the test sample 4. For a well designed slotted plate 16, the main contribution to the currents 8 in the test sample 4 are the image currents 18 induced by currents travelling in the slotted plate 16, which in places are physically very close to the test sample 4 and therefore induce strong current flows. The currents 18 in the slotted plate 16 are themselves the image currents from the winding 2, which are induced very strongly into the slotted plate 16 at its top surface where the winding 2 is close to the slotted plate 16. The net effect is that the currents 8 induced in the test sample 4 can be enhanced compared to an arrangement having the same distance between the winding 2 and the test sample 4 but not incorporating a slotted plate 16.

Fig. 6 shows the effect on the DC magnetic field pattern of introducing a ferromagnetic slotted plate 16 between the winding 2 and test sample 4 for the arrangement in Fig. 3. The slotted plate 16 modifies the DC field pattern in the test sample 4, but, by positioning the slots below the boundaries between magnets 12, the field pattern in the test sample 4 is broadly similar to the pattern 14

of Fig. 3. With a well-designed ferromagnetic slotted plate 16, the field intensity in the test sample 4 can be made considerably larger than the field in the absence of the slotted plate 16, for equivalent distance between

5 magnets and test sample.

Fig. 6 shows the key components of a horizontally polarised shear wave EMAT with a slotted wear plate 16. The DC field pattern 20 in the test sample, shown in Fig. 6, and the AC current pattern 8 in the test sample 4, which  
10 will be the same as shown in Fig. 5, create the required lorentz forces. The proviso is that the wear plate 16 must be electrically conductive, ferromagnetic and have slots whose geometry enhances both the AC image currents and the DC magnetic fields of the EMAT.

15 Fig. 5 and 6 illustrate one particular type of EMAT only, but the principle of using a slotted conductive and ferromagnetic wear plate 16 is applicable to other designs, albeit with different slot arrangements.

Fig. 7 shows in more detail part of an EMAT according  
20 to the invention. The slotted plate 16 is in the form of a grill or grid with the AC winding 2 and the DC magnets 12 contained within a housing 20. The winding 2 comprises a C-core 22 although other configurations may be used.

By way of further explanation, the affect of a  
25 conductive or ferromagnetic wear layer on an EMAT is

influenced by variation of the electrical and magnetic properties over the face area of the wear plate. The most easily controlled variation is produced by removal of material from specific areas of the wear plate, for example by cutting slots. The resulting electrical discontinuities across the wear face alter greatly the degree to which the high frequency magnetic field interacts with the test material. The associated magnetic permeability variations also influence the DC flux pattern imposed by the EMAT. Importantly, the joint action of the high frequency induced currents in the EMAT wear plate and the DC fields in the wear plate can play a novel role in enhancing the EMAT acoustic performance. By careful design, the wear plate can be arranged so that the EMAT performance is greatly increased compared to an EMAT with a conventional wear plate of similar thickness, subject to constraints due to the need for mechanical robustness. The material of the wear plate can then be selected to achieve greatly improved mechanical protection of the EMAT compared to a conventional wear material. The final design must also take into account the acoustic signals generated within the wear plate by EMAT action and any adverse affects caused by them.

AC field effects

The wear plate influences the EMAT performance in several ways. One of these is that it changes the AC fields and eddy currents within and around the EMAT and test material. Currents flowing within the wear plate are particularly important. The magnitude and surface area of high frequency eddy currents flowing adjacent the test material on the outer face of the wear plate are very significant and must be oriented correctly and maximized for best wear plate design.

To optimize the AC eddy currents within the wear plate, slots should be cut into the wear plate transversely to the eddy current flow lines occurring on the inward facing (winding side) surface of the wear plate. The spacing of these slots and their lengths must ensure that current flows that remain on the inside surface of the wear plate, moving transversely to the slots, are forced to circulate by traveling down the slot walls and along the outer surface of the wear plate in the opposite direction to the flow on the inner surface. Any alternative current loops that circulate entirely within the inner surface plane of the wear plate, not reaching the outer surface, must be prevented since these currents do not contribute to the acoustic performance of the EMAT and waste electrical energy.

An important means of reducing the wasteful AC currents circulating entirely within the inner surface plane is by extending the slots well beyond the most intense AC fields of the EMAT. This ensures that the eddy currents existing in the region beyond the slots, where they are more free to circulate within the inner plane, are weak and of little relevance to EMAT efficiency. An additional method of reducing AC currents at the inner surface is to decrease the distance between slots in regions close to the poles of the AC winding, where by definition AC flux has a significant component normal to the inner surface and the eddy currents prefer to circulate parallel to the inner plane.

The desired AC currents that flow on the outer surface of the wear plate behave like an additional electrical winding, complementing the main winding of the EMAT. Since these currents flow in a plane that is physically adjacent the test material, they induce stronger image currents in the test material than those produced directly by the main winding of the EMAT, which is more distant from the test material due to the presence of the wear plate. The

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performance of the EMAT is approximately proportional to the magnitude of the outer surface currents in the wear plate.

To ensure the desired circulation of currents, the wear plate electrical conductivity must be high and the wear plate thickness should be significantly larger than the electrical skin depth associated with the wear plate material at the operating frequency of the EMAT. However, the thickness should not be so great that the currents flowing down the walls of the slots, normal to the plane of the wear plate, encounter too much electrical resistance to allow useful current magnitudes to develop.

The AC current flows in the wear plate for any given winding arrangement, and overall plate dimensions can be optimized for acoustic effect by an appropriate design of slot pattern. However the slot pattern cannot be finalized without considering other factors, one being its impact on the DC field performance of the EMAT.

#### DC field effects.

The performance of virtually all EMATs improves with increase in the DC field strength generated within the test sample. The DC field strength is affected by the slot distribution and is optimized by arranging slots to coincide with boundaries of the DC magnetic pole faces on the front surface of the EMAT. With this arrangement, DC flux is forced to circulate by crossing the thickness of the wear plate and closing via the test specimen.

Conversely the flux is prevented from travelling pole to



pole within the wear plate since this would involve crossing a slot, which obstructs flux because it is a region of much reduced permeability. Essentially the wear plate must act as a conventional pole piece for the permanent magnet array of the EMAT (or the low frequency field arrangement that sometimes substitutes for the permanent magnets).

Note that the DC field requirements can conflict with the mechanical integrity of the wear plate.

#### 10 Mechanical integrity

The DC rules for slot configuration cannot be implemented rigorously since the slots would then form closed loops as they trace out the boundary of the pole areas on the transducer face. This would divide the wear plate into disconnected parts and undermine the mechanical integrity of the plate. For example, in the case of a single pole EMAT, the slot would form a ring leaving a large central section of wear plate unsupported by the remaining plate and requiring the inconvenience of a separate means of support. A compromise on the ideal DC field design of the slots is therefore required in most practical cases.

Another factor influencing slot design is that a slot having an axis parallel to the intended travel direction of the EMAT may be preferential to a slot transverse to the

travel direction under certain wear conditions. This is especially true if there are many closely spaced slots and the EMAT is likely to encounter objects that are capable of gouging the transducer face. The adverse consequence of having transverse closely spaced slots is that the thin ligaments of material between slots may become deformed due to the forces generated during gouging.

#### Acoustic effects

The thickness and other dimensions of the wear plate influence the amplitude of acoustic waves caused by direct acoustic generation by the EMAT into the wear plate. These waves must be arranged so that they do not adversely affect the operation of the EMAT. Long-lasting reverberations within the wear plate that mask the reception of acoustic signals from the test material must be prevented.

The ideal wear plate thickness is one quarter the wavelength of the main wave mode excited within the wear plate. At this thickness the wear plate will not support normally-directed standing waves, which could resonate significantly after pulse transmission and create signals for which the EMAT would be particularly sensitive. Acoustic damping materials placed in contact with the wear plate are sometimes necessary to reduce the acoustic excitation of the wear plate. This requirement is less important where the EMAT is operating exclusively as a

transmitter or exclusively as a receiver. Under these circumstances there can be no problem in which transmission pulse reverberation affects received signals (so called ring-down).

## 5 General

The wear plate slot arrangement should therefore take into account the AC field behaviour, the DC field behaviour and mechanical issues, namely the avoidance of partitioning the plate into isolated parts and giving due consideration to the travel direction of the EMAT and the damaging events that may occur. The wear plate thickness and general design should take into account the acoustic activity generated internally within the wear plate and its impact on EMAT acoustic performance. The material of the wear plate should have the necessary permeability and conductivity for satisfactory control of AC currents within the wear plate, and must be abrasion resistant.

It can be shown from the AC and DC field considerations that the slotted wear plate is most suited to EMATs where the slot pattern can be directed parallel to the forces to be generated in the test sample. Consequently

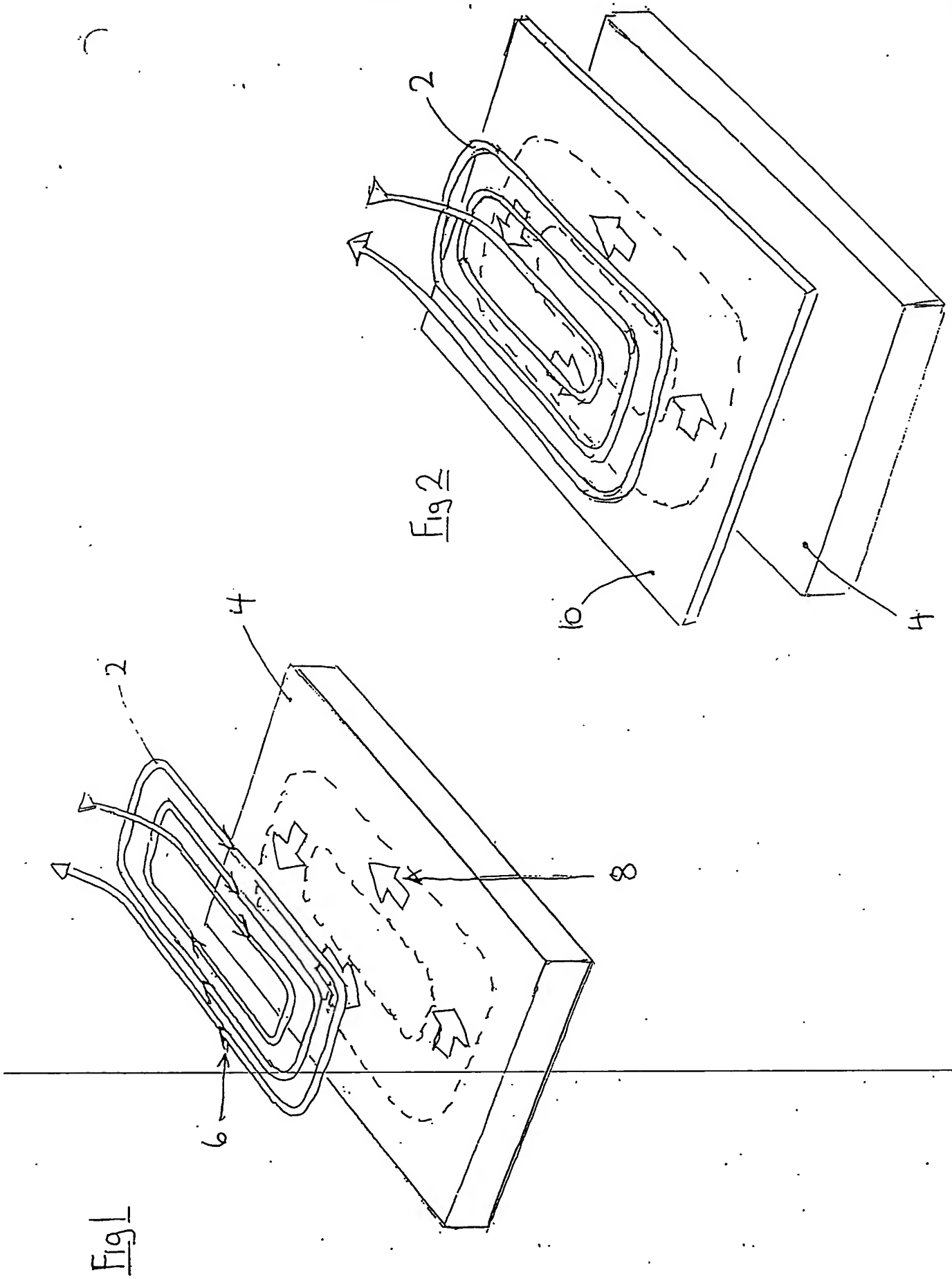
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the slotted wear plate is most suited to various forms of shear wave transducer, in which the desired forces, like the slot axes, are parallel to the surface of the test sample. (Note that the force direction is not the same as

the wave propagation direction, for which there are no constraints other than those intrinsic to EMAT transducers). The most important transducer types for which the wear plate is suited are the linearly and radially polarized shear wave transducers, for wall thickness measurement, and horizontally polarized shear wave transducers, for angled or guided shear wave propagation. EMATs that generate forces normal to the surface of the test material are less suited to the use of the slotted wear plate since for these there is a conflict between the optimum AC and optimum DC orientation of the slots.

An EMAT having a wear plate constructed from 3mm thick tool steel has achieved equivalent acoustic performance to a previous design in which the EMAT was protected by a 0.5mm thick ceramic layer and which was proved to be insufficiently robust for pipeline inspection purposes.

Thus there is provided an EMAT the wear plate of which is of a ferromagnetic and electrically conductive material configured so as to have material discontinuities advantageous to the acoustic performance of the EMAT through its effect on both the DC and AC field components generated by the EMAT.



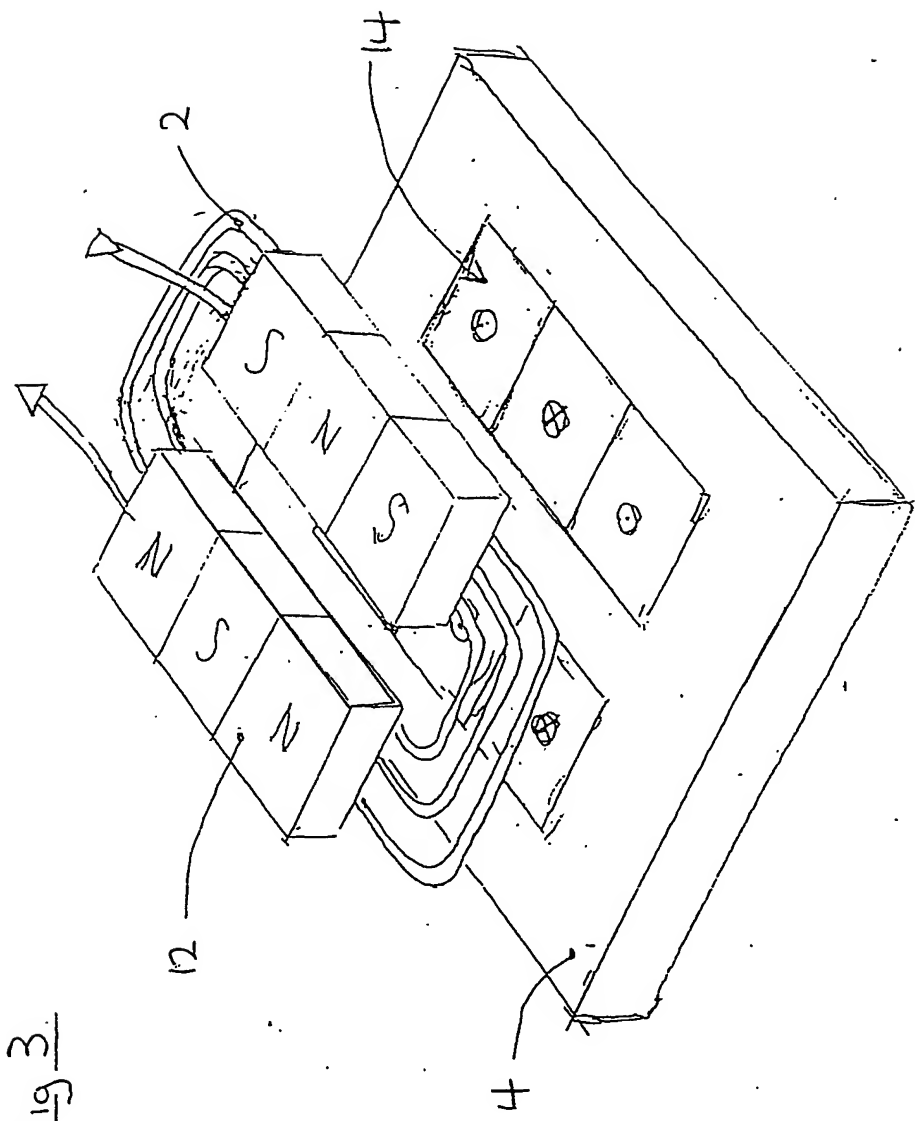


Fig 3

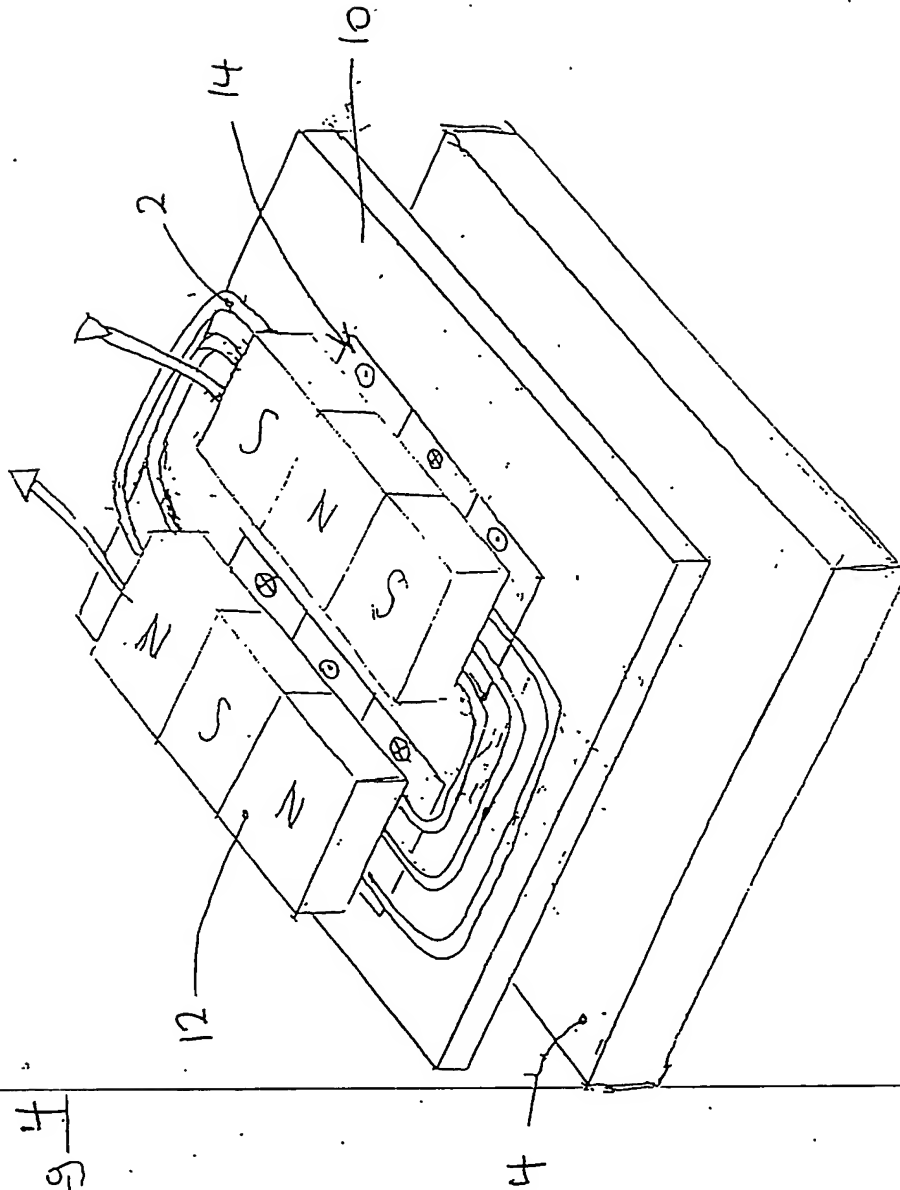
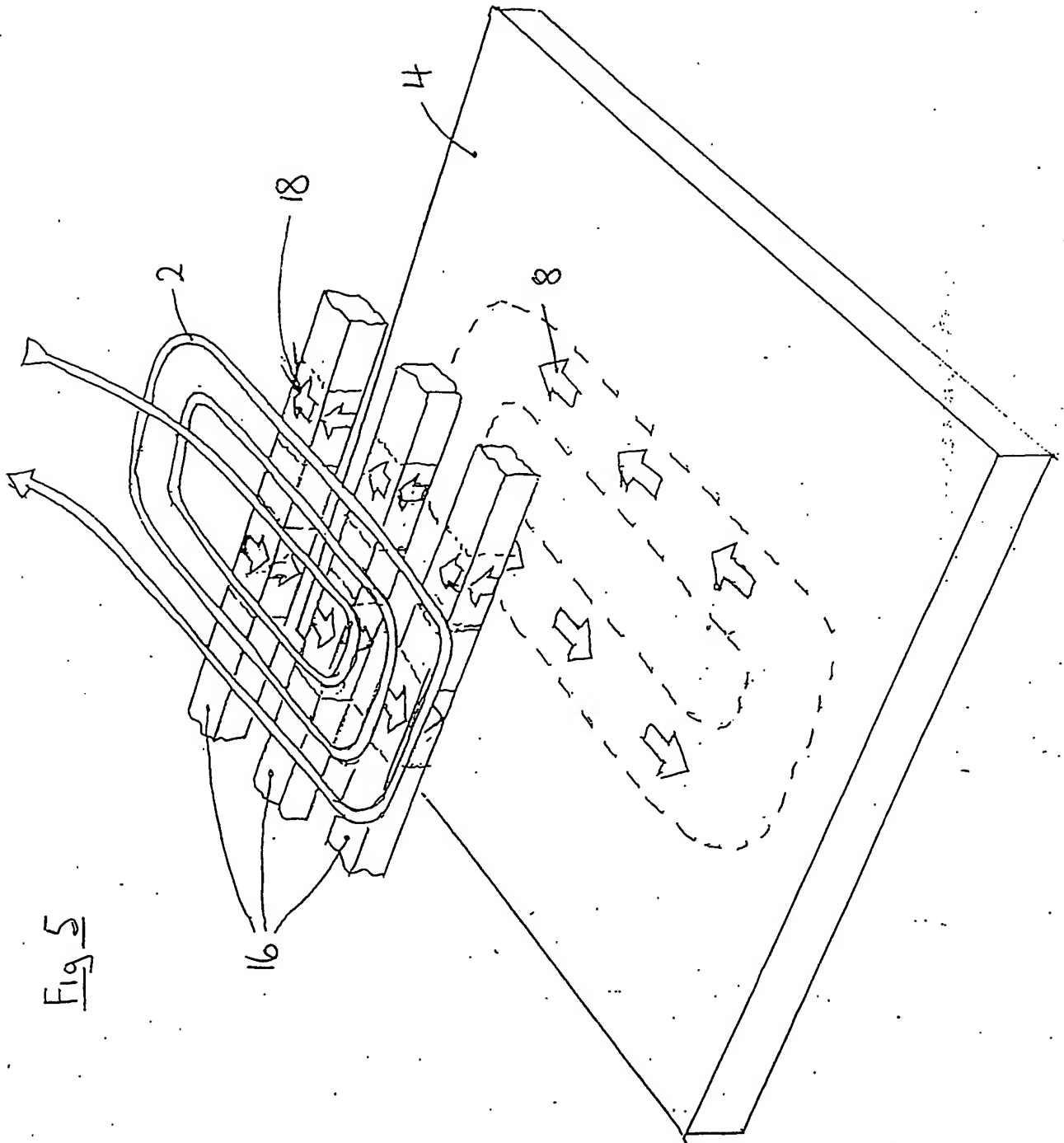


Fig 4





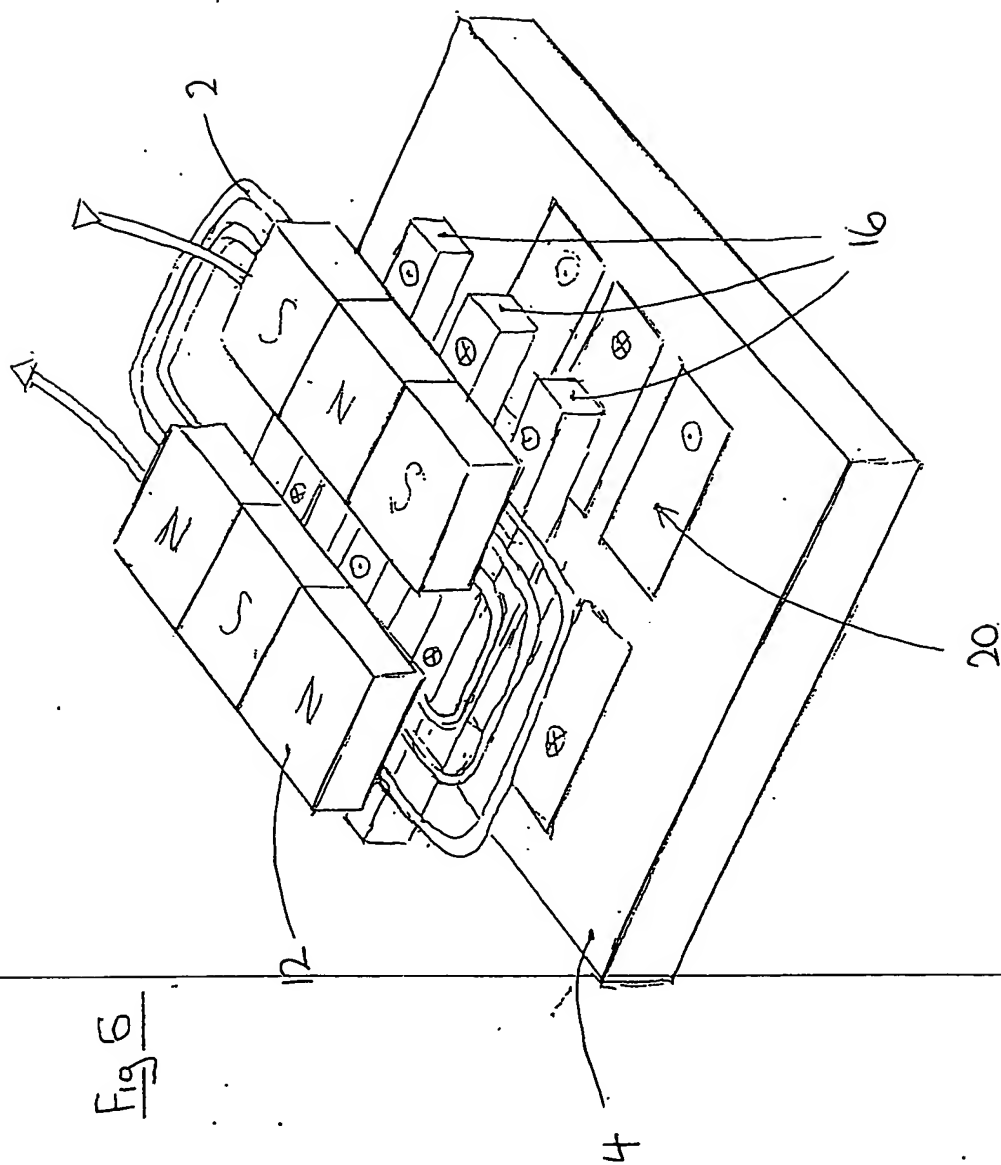


Fig 5

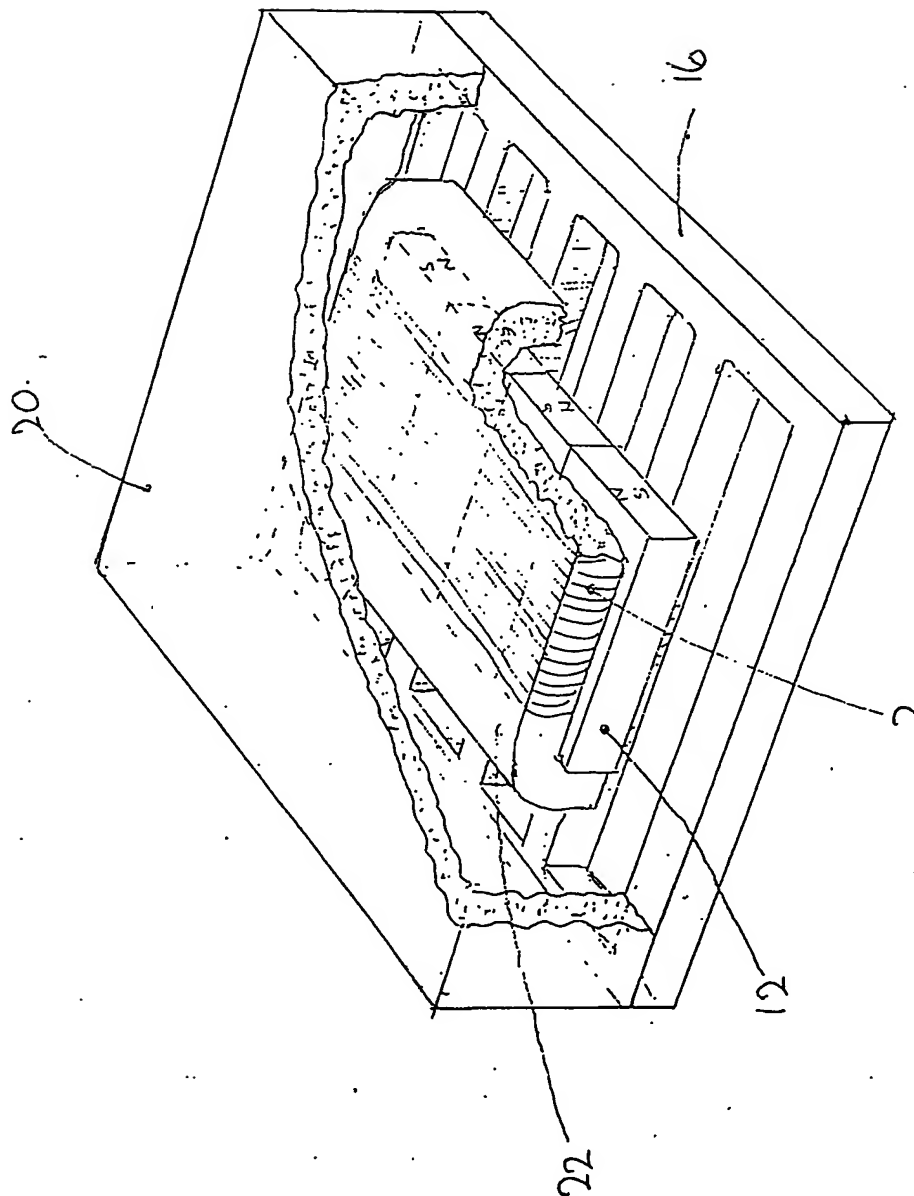


FIG. 7

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